

Mulching mode and planting density affect canopy interception loss of rainfall and water use efficiency of dryland maize on the Loess Plateau of China

ZHENG Jing^{1,2}, FAN Junliang^{1,2*}, ZHANG Fucang^{1,2}, YAN Shicheng^{1,2}, GUO Jinjin^{1,2}, CHEN Dongfeng^{1,2}, LI Zhijun^{1,2}

¹ Key Laboratory of Agricultural Soil and Water Engineering in Arid and Semiarid Areas of Ministry of Education, Northwest A&F University, Yangling 712100, China;

² Institute of Water-saving Agriculture in Arid Areas of China, Northwest A&F University, Yangling 712100, China

Abstract: High and efficient use of limited rainwater resources is of crucial importance for the crop production in arid and semi-arid areas. To investigate the effects of different soil and crop management practices (i.e., mulching mode treatments: flat cultivation with non-mulching, flat cultivation with straw mulching, plastic-covered ridge with bare furrow and plastic-covered ridge with straw-covered furrow; and planting density treatments: low planting density of 45,000 plants/hm², medium planting density of 67,500 plants/hm² and high planting density of 90,000 plants/hm²) on rainfall partitioning by dryland maize canopy, especially the resulted net rainfall input beneath the maize canopy, we measured the gross rainfall, throughfall and stemflow at different growth stages of dryland maize in 2015 and 2016 on the Loess Plateau of China. The canopy interception loss was estimated by the water balance method. Soil water storage, leaf area index, grain yield (as well as its components) and water use efficiency of dryland maize were measured or calculated. Results showed that the cumulative throughfall, cumulative stemflow and cumulative canopy interception loss during the whole growing season accounted for 42.3%–77.5%, 15.1%–36.3% and 7.4%–21.4% of the total gross rainfall under different treatments, respectively. Soil mulching could promote the growth and development of dryland maize and enhance the capability of stemflow production and canopy interception loss, thereby increasing the relative stemflow and relative canopy interception loss and reducing the relative throughfall. The relative stemflow and relative canopy interception loss generally increased with increasing planting density, while the relative throughfall decreased with increasing planting density. During the two experimental years, mulching mode had no significant influence on net rainfall due to the compensation between throughfall and stemflow, whereas planting density significantly affected net rainfall. The highest grain yield and water use efficiency of dryland maize were obtained under the combination of medium planting density of 67,500 plants/hm² and mulching mode of plastic-covered ridge with straw-covered furrow. Soil mulching can reduce soil evaporation and retain more soil water for dryland maize without reducing the net rainfall input beneath the maize canopy, which may alleviate the contradiction between high soil water consumption and insufficient rainfall input of the soil. In conclusion, the application of medium planting density (67,500 plants/hm²) under plastic-covered ridge with bare furrow is recommended for increasing dryland maize production on the Loess Plateau of China.

Keywords: dryland maize; throughfall; stemflow; canopy interception loss; yield; water use efficiency; Loess Plateau

*Corresponding author: FAN Junliang (E-mail: nwwfjl@163.com)

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1 Introduction

Incident gross rainfall is intercepted by crop canopy as it moves towards the ground and it can be partitioned into three components: throughfall, stemflow and canopy interception loss (Lamm and Manges, 2000; Carlyle-Moses, 2004). Throughfall, considered as the portion of rainfall that reaches the ground through the canopy gaps or leaf raindrops, is the major water flux within most agricultural systems (Dunkerley, 2000). Stemflow, which refers to the part of rainfall that flows down the plant stem and subsequently delivers to the root zone (Lamm and Manges, 2000), is usually important to maintain the water balance of plant species and alleviate the drought stress on plant growth (Levia and Frost, 2003; Swaffer et al., 2014). Canopy interception loss, the proportion of rainfall that is intercepted, reserved and eventually evaporated back into the atmosphere during and after rainfall events (Fan et al., 2014; Li et al., 2015), is a significant and sometimes dominant component of rainwater loss in farmland ecosystems. It reduces the amount of actual effective rainfall reaching the ground surface. These studies indicate that the canopy interception loss cannot be ignored. Numerous studies have quantified various redistribution processes under maize crop canopy (Steiner et al., 1983; Paltineanu and Starr, 2000; Wang et al., 2006; Han et al., 2014). The percentages of canopy interception loss to total rainfall input are not consistent at different locations in the world, which are related to differences in canopy structure (e.g., leaf area index and leaf shape) and meteorological conditions (e.g., rainfall intensity, wind speed, relative humidity and solar radiation) (Shi et al., 2010; Ghimire et al., 2012; Fathizadeh et al., 2014; Fan et al., 2018a, b).

The Loess Plateau is one of the most important regions of agricultural production (including the maize production) in China. Rainfall scarcity, especially during the growth season of dryland maize, is a major problem in this region (Wang et al., 2011). The key to increase agricultural productivity depends on how to maximize the utilization of limited rainfall resource. In semi-arid regions of the Loess Plateau, many agronomic practices have been explored over the past decades, especially for the dryland maize (Liu et al., 2010; Li et al., 2013). Mulching mode and planting density greatly affect the growth and grain yield of dryland maize, and their effects have been well documented (Tokatlidis et al., 2011; Zhou et al., 2011; Yin et al., 2017). If the planting density is too high, it will reduce the availability of incident rainfall in the growing season and intensify rainfall resource pressure. Mulching mode can be used to explore the problems of water shortage and rainfall fluctuation by altering the balance between evaporation and transpiration (Pabin et al., 2003; Deng et al., 2006), which may efficiently improve the crop growth conditions and then in turn affect the input of net rainfall. However, the effects of mulching mode and planting density on the rainfall partitioning by dryland maize canopy, especially the resulted net rainfall input beneath the maize canopy, were generally neglected and seldom studied.

Improving knowledge of the agricultural water cycle in dryland agriculture, therefore, is of crucial importance for the high and efficient use of limited rainwater resource. The objectives of this study were: (1) to evaluate the percentages of throughfall, stemflow and canopy interception loss at different growth stages of dryland maize under different planting modes; and (2) to explore the effects of mulching mode and planting density on the partitioned rainfall components, grain yield and water use efficiency (WUE) of dryland maize on the Loess Plateau of China.

2 Materials and methods

2.1 Study area

The field experiment was carried out at the Water-saving Station of the Key Laboratory of Agricultural Soil and Water Engineering (34°18'N, 108°04'E; 521 m a.s.l.), sponsored by the Ministry of Education, at the Northwest A&F University, Loess Plateau of China. This area is characterized by a warm temperate and monsoon climate, and situated in a semi-arid to semi-humid transition zone. The maximum and minimum air temperatures in this area are 42.0°C and -19.4°C, respectively, and the annual mean air temperature is 12.9°C. The total annual sunshine hour is 2196

h and the frost-free period is 220 d. The mean annual pan evaporation is 1500 mm, and the mean annual precipitation is 560 mm, with 65% of the total precipitation falling between June and September. The soil of the experimental field is silty clay loam in texture, with a mean bulk density of 1.40 g/cm^3 in the top soil layer (0–50 cm). The field water holding capacity and permanent wilting point of the soil were 24.0% and 8.5% (gravimetric), respectively. The groundwater level is at least 50 m below the soil surface; thus, the capillary rise from groundwater can be neglected in the present study (Ji et al., 2014). The total rainfall during the growing season of dryland maize (from mid-June to early October) amounted to 270 mm in 2015 and 261 mm in 2016 (Fig. 1), both of which were lower than the long-term mean seasonal rainfall of 333 mm.

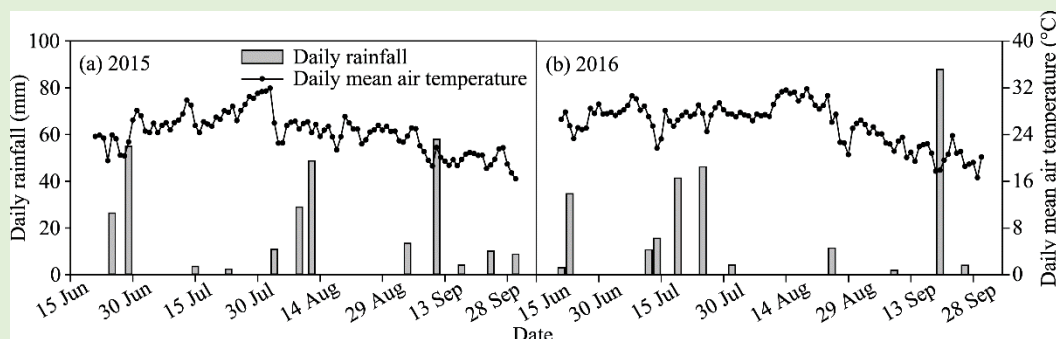


Fig. 1 Daily rainfall distribution and daily mean air temperature during the growing seasons of dryland maize in 2015 (a) and 2016 (b)

2.2 Experimental design

"Zhengdan 958", a popular maize cultivar in the study area, was used in the experiment. Four types of mulching mode (NM, flat cultivation with non-mulching; SM, flat cultivation with straw mulching; RP, plastic-covered ridge with bare furrow; RPFS, plastic-covered ridge with straw-covered furrow) and three levels of planting density (LD, low planting density of 45,000 plants/hm²; MD, medium planting density of 67,500 plants/hm²; HD, high planting density of 90,000 plants/hm²) were applied in this study. The twelve treatments (four mulching modes \times three planting density levels) were replicated three times in a randomized complete factorial block design. Each field plot was designed as 15 m², containing 6 rows with each row being 5.0 m long. To prevent the lateral spread of water, we surrounded the plots by dikes with a distance of 1.5 m between plots. In the experiment, the straw mulch material was wheat straw. Alternated ridges and furrows were prepared by shaping the soil surface before planting maize. Ridges (60.0 cm wide and 15.0 cm high) were covered with plastic film (80.0 cm wide and 0.008 mm thick), while furrows (60.0 cm wide) were not mulched or mulched with wheat straw. A double row of maize was planted in furrows. Wheat straw was cut into 15.0 cm long segments and was covered the next day after sowing. The wheat straw was uniformly applied at a rate of 9000 kg/hm² over the entire soil surface with the SM treatment or in furrows with the RPFS treatment (Cai et al., 2011). Different planting densities (LD, MD and HD) were employed by changing plant spacing of 37.0, 25.0 and 18.5 cm, respectively, with a fixed row spacing of 60.0 cm. The maize was sown on 15 June 2015 and 12 June 2016, and harvested on 30 September 2015 and 5 October 2016, respectively. Fertilizers N, P₂O₅ and K₂O were applied as basal fertilizers at a rate of 180 kg/hm², 120 kg/hm² and 60 kg/hm², respectively. No fertilizer or irrigation was further applied during the whole growth season. Other management practices, including pest and weed control were undertaken according to local agronomic practices.

2.3 Data collection

2.3.1 Measurements and calculations of gross rainfall and its components

The gross rainfall was measured by a standard rain gauge with a resolution of 0.1 mm and a mini logger recording 60-min rainfall amount from an automatic weather station (HOBO event logger, USA) located approximately 25.0 m from the experimental field. The gross rainfall was measured

by four collecting containers (10.0 cm in diameter and 15.0 cm in height) around the experimental field at the same time. The rainfall volume was collected and measured at once after each rainfall event. A rainfall event was defined as a rainfall period from preceding and succeeding rainfall being partitioned by at least 6 h without rainfall.

Throughfall was measured using 15 collecting containers located beneath four adjacent maize plants which were selected randomly at each experimental plot (Fig. 2). The throughfall volume was measured promptly after each rainfall event. Then, it was converted into depth by dividing the horizontal cross-sectional area of the collecting container (Tanaka et al., 2015). There were three replicates for each throughfall measurement. The relative throughfall was calculated as: (throughfall/gross rainfall)×100%.

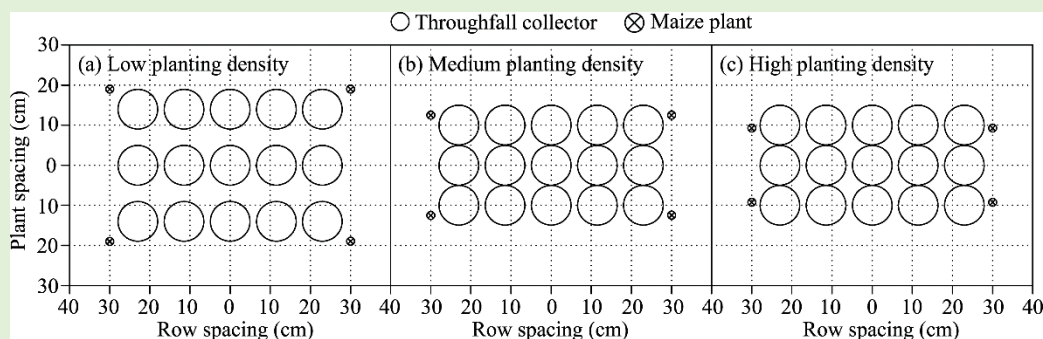


Fig. 2 Schematic layout of collecting containers for throughfall measurement under different planting densities

Stemflow was measured on six maize plants which were representative of the experimental plots. The stemflow was collected using collars constructed from plastic plates that were fitted around the maize stem. Furthermore, we designed a slot with a transfer hose to drain the stemflow water from the stemflow collars to the collecting containers which held the accumulated stemflow (Lamm and Manges, 2000). The stemflow volume was measured using a graduated cylinder after each rainfall event. The equivalent stemflow depth was calculated using Equation 1:

$$S_d = \frac{V_s}{A}, \quad (1)$$

where S_d is the stemflow depth (mm); V_s is the stemflow volume (L); and A is the average ground area occupied by a maize plant (m^2). The relative stemflow was calculated as: (stemflow/gross rainfall)×100%.

The interception loss by the canopy of maize for each rainfall event was calculated from the water balance method (Fan et al., 2015; Zhang et al., 2015):

$$I = G - P_n, \quad (2)$$

$$P_n = T + S_d, \quad (3)$$

where I is the canopy interception loss (mm); G is the gross rainfall (mm); P_n is the net rainfall during a rainfall event (mm); and T is the throughfall (mm). The relative canopy interception loss was calculated as: (canopy interception loss/gross rainfall)×100%.

The cumulative throughfall, cumulative stemflow and cumulative canopy interception loss were calculated as the sum of individual rainfall value over the whole growing season of dryland maize. Percentages of cumulative throughfall, cumulative stemflow and cumulative canopy interception loss during the growing season of dryland maize were calculated.

2.3.2 Measurement and calculation of leaf area index (LAI)

For each treatment, three plants with three replicates were randomly selected to measure the leaf area every 5–10 d. The total leaf area of a single maize plant was calculated by Equation 4 (Qi et al., 2012):

$$LA = \sum_{i=1}^n k \times L_i \times W_i, \quad (4)$$

where LA is the total leaf area of a single maize plant (cm^2); n is the number of green leaves on a single maize plant; k is a correction coefficient ($k=0.75$); L_i is the length of the i^{th} leaf (cm); and W_i is the maximum width of the i^{th} leaf (cm).

LAI (m^2/m^2) was calculated as follows:

$$LAI = 0.0001N \times LA, \quad (5)$$

where N is the number of maize plants per unit ground area.

2.3.3 Measurement of soil water content

To calculate changes in soil water storage of the soil profile throughout the whole growing season, we measured soil water content gravimetrically at depths of 0–20, 20–40, 40–60, 60–80, 80–100, 100–125, 125–150 cm before sowing and after harvesting of maize in the two experimental years (2015 and 2016). In addition, we measured the water content of the soil profile at the middle of each growth stage (i.e., 3 July, 24 July, 15 August, 11 September and 23 September in 2015 and 27 June, 23 July, 17 August, 7 September and 22 September in 2016) to observe the dynamics of soil water storage. The sampling positions for cultivation with ridge and furrow were located in the middle of furrow, in the middle of ridge and at the boundary of two adjacent ridge and furrow. For flat cultivation, soil samples were collected close to the maize plants and between two adjacent plant rows. And, all measurements had three replicates. Gravimetric soil water content and dry bulk density were obtained by oven-drying the samples at 105°C . Gravimetric soil water content was multiplied by soil bulk density to obtain the volumetric soil water content. Soil water storage was calculated by multiplying the volumetric soil water content by soil profile depth in the upper 150 cm soil layer.

2.3.4 Grain yield, yield components and water use efficiency (WUE)

Grain yield and yield components were investigated from the center of each plot at physiological maturity of the 30 collected ears. Head length and seed number per head were measured for all harvested ears. Three samples of 1000 kernels were oven-dried at 80°C for three days to constant weight, and then weighted to estimate the 1000-seed weight. All the kernels were air-dried and the grain yield was determined at a 14.0% soil water content basis. Seasonal evapotranspiration for each plot was determined by the following soil water balance equation (Bu et al., 2013; Fan et al., 2016):

$$ET = P_n + \Delta S, \quad (6)$$

where ET is the seasonal evapotranspiration (mm); and ΔS is the change in soil water storage (mm), without considering surface runoff due to flat soil surface or deep percolation as a result of low rainfall and great soil water-holding capacity in the upper 150 cm layer. WUE ($\text{kg}/(\text{hm}^2 \cdot \text{mm})$) was further calculated as maize yield (Y (kg/hm^2)) divided by seasonal water use (evaluated as ET in the present study), i.e., $\text{WUE} = Y/ET$.

2.4 Statistical analysis

Analysis of variance was performed to determine the effects of mulching mode, planting density and their interactions on canopy interception loss of rainfall and water use efficiency of dryland maize using statistical software SPSS 16.0 (SPSS Inc., Chicago, USA). Least significant difference test was used to detect differences among the means of treatments. Differences were considered statistically significant at $P < 0.05$ level. The figures were plotted with SigmaPlot 10.0 Software (Systat Software Inc., San Jose, IL, USA).

3 Results and discussion

3.1 Effects of mulching mode and planting density on leaf area index (LAI) of maize

Figure 3 shows the LAI dynamics of dryland maize at different growth stages in the two experimental years (2015 and 2016). For all treatments, LAI firstly increased and peaked at the tasseling stage of dryland maize (12 August in 2015 and 2 August in 2016). Subsequently, LAI

decreased because of leaf senescence at the late stage of maize growth (11 and 24 September in 2015; and 9 and 26 September in 2016). The differences in LAI under different mulching modes were gradually obvious with the advance of growth stages. Among the four mulching modes, LAI was highest under RPFS, followed by RP, SM and NM, which was similar to previous studies of Chen et al. (2002) and Wang et al. (2004). Compared with NM, RPFS and RP respectively increased the averaged LAI of the whole growing seasons in 2015 and 2016 by 36.2% and 23.6%, while SM increased the averaged LAI by 12.8%. Planting density had a higher effect on LAI than mulching mode, implying that it is a dominant influencing factor on LAI. Compared with LD, MD and HD increased the averaged LAI of the whole growing season in 2015 and 2016 by 63.8% and 86.9%, respectively.

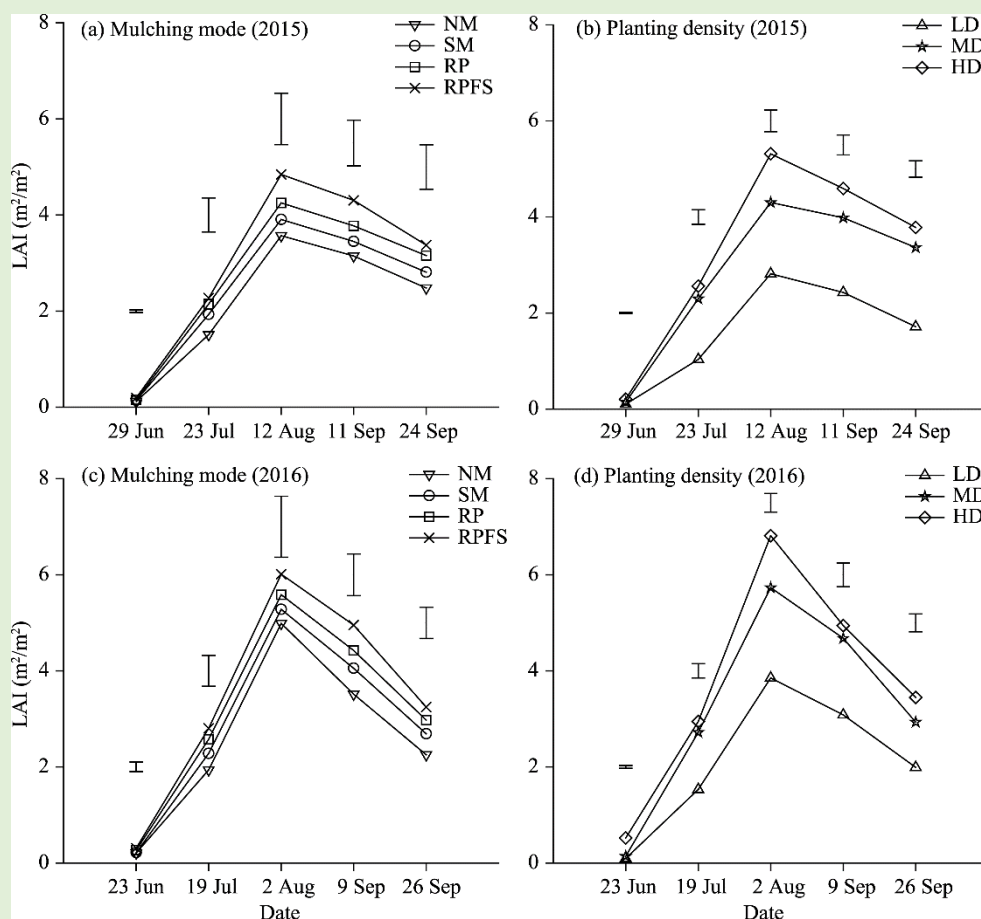


Fig. 3 Dynamics of leaf area index (LAI) of dryland maize under different mulching modes and planting densities in 2015 and 2016. NM, flat cultivation with non-mulching; SM, flat cultivation with straw mulching; RP, plastic-covered ridge with bare furrow; RPFS, plastic-covered ridge with straw-covered furrow; LD, low planting density (45,000 plants/hm²); MD, medium planting density (67,500 plants/hm²); HD, high planting density (90,000 plants/hm²). Vertical bars indicate significant difference at $P < 0.05$ level.

Water scarcity is an essential limiting factor for crop production and soil water content is remarkably affected by precipitation in the rainfed regions of China (Kang et al., 2000). Sufficient rainfall can supplement the soil water, thereby improving the crop growth due to the increase in LAI. The overall LAI in 2016 was higher than that in 2015 (Fig. 3), which was due to more rainfall at the early stage of maize growth in 2016. The averaged LAI in 2016 was 17.4% higher than that in 2015. At the late stage of maize growth, LAI was decreased by 49.0% in 2016, which was greater than that (28.7%) in 2015. The large decrease in LAI at the late stage in 2016 was mainly due to severe drought stress at the tasseling stage, resulting in more leaf senescence in dryland

maize. Our results were in good agreement with those of Jia et al. (2018), who also found that water deficit in the dryer year caused the premature leaf senescence.

3.2 Effects of mulching mode and planting density on redistribution of rainfall

At the growth stages of dryland maize in the two experimental years, the relative throughfall was highest under NM treatment, followed by SM, RP and RPFS treatments (Fig. 4). For the four mulching modes, the relative stemflow and canopy interception loss values were ranked as $NM < SM < RP < RPFS$ at different growth stages of dryland maize in both years (Figs. 5 and 6). Generally, surface mulching benefits the growth of leaves to a certain extent and promotes the occurrence of shelters for rainfall (Liu et al., 2015), which thus increasing the capability of intercepting and collecting rainfall and converting it into stemflow. Table 1 shows that mulching mode had no significant effect on the amount of net rainfall in the two experimental years. The canopy interception loss was not significantly changed among the four mulching modes (Fig. 6c), which may be due to the insignificant differences in LAI. Also, incident gross rainfall tended to spill over toward the edge of the canopy to generate drip points or be converted into stemflow rather than leaf surface evaporation under a saturated canopy. This can be largely attributed to the special shape of maize leaves, which resulted in an insignificant difference in net rainfall in both years. Furthermore, the compensation between throughfall and stemflow among the four mulching modes may also explain why there was no significant difference of net rainfall.

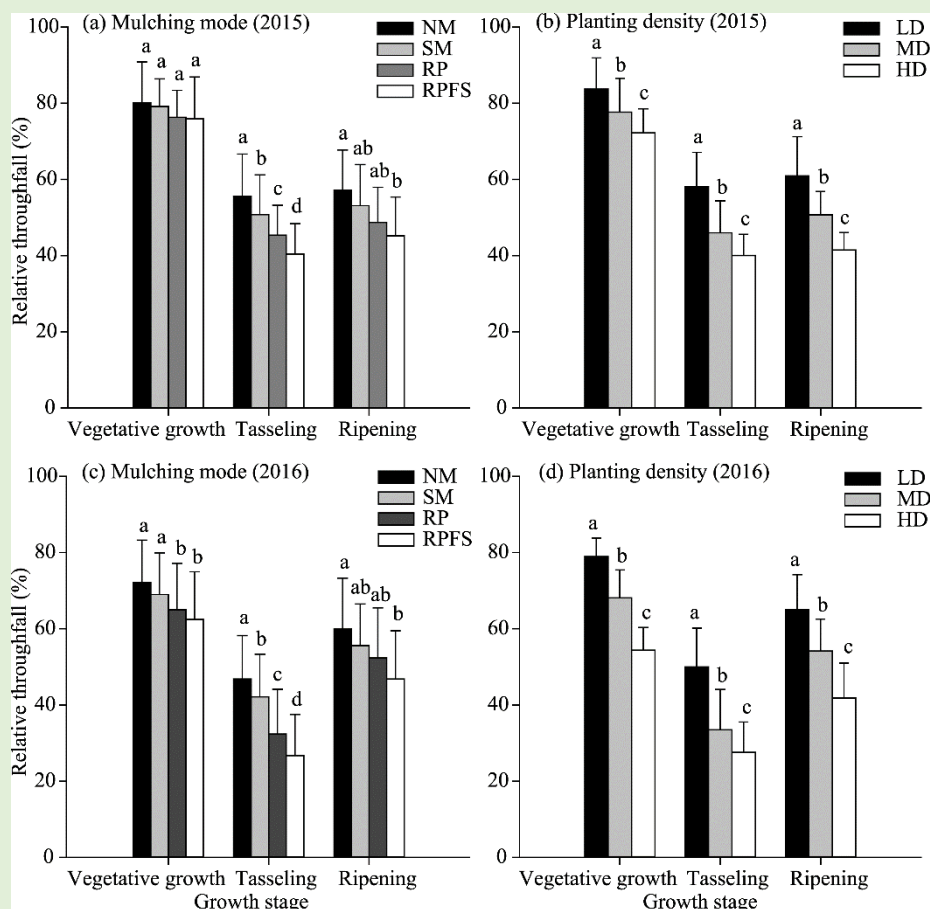


Fig. 4 Relative throughfall at different growth stages of dryland maize under different mulching modes and planting densities in 2015 and 2016. Different lowercase letters indicate significant differences among treatments at $P < 0.05$ level at the same growth stage. Error bars represent standard deviations.

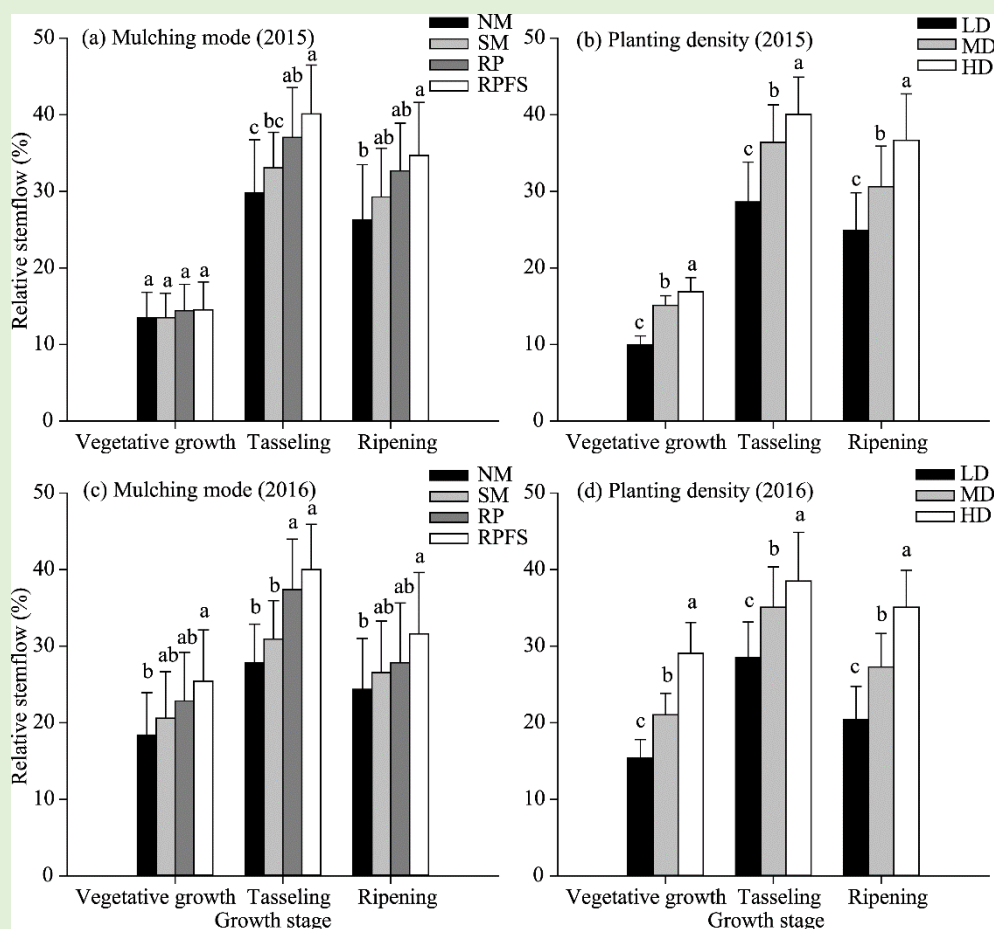


Fig. 5 Relative stemflow at different growth stages of dryland maize under different mulching modes and planting densities in 2015 and 2016. Different lowercase letters are significantly different among treatments at $P < 0.05$ level at the same growth stage. Error bars represent standard deviations.

The relative throughfall significantly decreased with increasing planting density at different growth stages of dryland maize in both years (Fig. 4). The magnitude of relative stemflow and canopy interception loss under different plant densities was in the order of $LD < MD < HD$ (Figs. 5 and 6). Our results are in agreement with the findings of previous studies by Quinn and Laflen (1983) and Lamm and Manges (2000). The catchment area varies according to the different planting densities which then affect the water distribution of the field (Liu et al., 2007). Planting density significantly affected the amount of net rainfall after the redistribution of canopy rainfall loss (Table 1). Many investigators have confirmed that there were significant correlations among relative throughfall, relative stemflow, relative canopy interception loss and LAI (Swaffer et al., 2014; Zhang et al., 2015; Ma et al., 2016). In this study, LAI of dryland maize significantly increased with increasing planting density. Therefore, the net rainfall amount tended to significantly decrease with the increase in planting density.

The relative canopy interception loss was highest at the ripening stage, which was not significantly different with the values at the tasseling stage. In 2016, the relative interception loss declined at the late growth stage, with the maximum occurring at the tasseling stage (Fig. 6). Generally speaking, the relative canopy interception loss under different mulching modes and planting densities increased steadily at the early stage but presented different change trends at the late stage, which was depended on crop growing conditions. Our findings in 2015 did not agree well with the results by Zheng et al. (2012) and Liu et al. (2015), who found that the relative canopy interception loss reached its maximum value at the tasseling stage. In our experiments, the

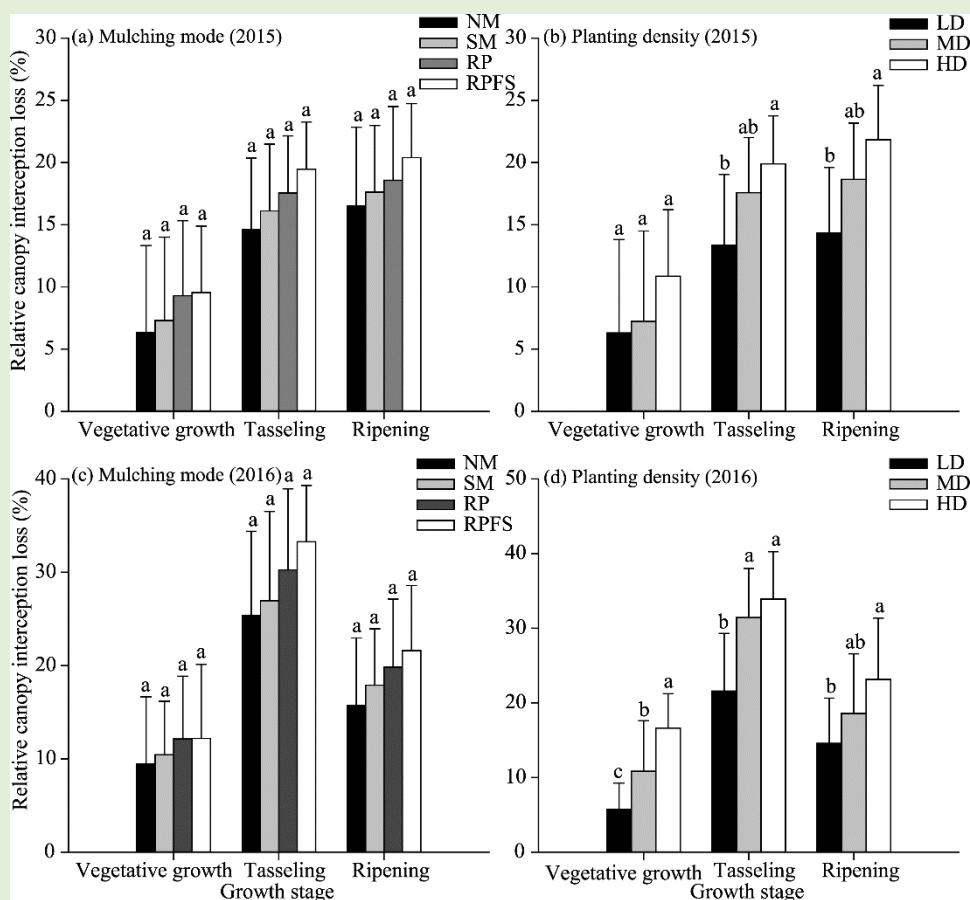


Fig. 6 Relative canopy interception loss at different growth stages of dryland maize under different mulching modes and planting densities in 2015 and 2016. Different lowercase letters are significantly different among treatments at $P < 0.05$ level at the same growth stage. Error bars represent standard deviations.

relative canopy interception loss maintained a relatively high stable value at the late stage of maize growth in 2015. Even the LAI decreased gradually due to the drying of leaves near the stem base at the late growth, the leaves at the bottom of the plants had not yet come off the maize plants. These leaves still played a role in the rainfall interception and thus maintained a higher relative canopy interception loss at the late stage of maize growth.

The percentage of cumulative throughfall measured in this study ranged from 42.3% to 77.5%, falling within the range of throughfall values reported previously (Quinn and Lafen, 1983; Steiner et al., 1983; Lamm and Manges, 2000; Wang et al., 2006; Han et al., 2014). However, the percentage of cumulative stemflow (15.1%–36.3%) and cumulative canopy interception loss (7.4%–21.4%) measured in this study were respectively lower and higher than the previously reported values. As we found earlier in Zheng et al. (2018), the relative stemflow and relative throughfall showed a decreased tendency with decreasing gross rainfall and rainfall intensity, while the decreasing rainfall amount and intensity resulted in an increase in relative canopy interception loss. The lower rainfall intensity (average of 11.8 mm/h) in our study resulted in a large amount of rainfall was intercepted and then evaporated during rainfall events and did not diverted to stemflow, leading to lower stemflow and higher canopy interception loss. Moreover, the higher canopy interception loss may be also ascribed to relative long rainfall duration. Low-density rainfall generally lasts for a long time, which could increase the canopy interception loss during the rainfall events (Norman and Campbell, 1983).

3.3 Effects of mulching mode and planting density on soil water storage

Obvious differences in soil water storage at 0–150 cm soil depth among different treatments at

various growth stages of dryland maize are shown in Figure 7. The three mulching treatments (RPFS, RP and SM), especially RPFS, conserved more water in the soil profile than NM at the vegetative growth stage (3 July and 24 July in 2015, and 27 June and 23 July in 2016). Compared with NM, the averaged soil water storage under RPFS, RP and SM treatments was respectively increased by 22.7, 16.7 and 9.8 mm at the vegetative growth stage in the two years. SM treatment can conserve soil water by reducing soil surface evaporation (Wang et al., 2011; Li et al., 2013). Incorporation of ridge and furrow can improve the soil water condition by collecting water from light rainfall, reducing unproductive evaporation and enhancing rainwater infiltration (Ren et al., 2008; Li et al., 2013). However, at the late stage of maize growth, field evapotranspiration was dominated by plant transpiration rather than soil evaporation. In 2015, RPFS and RP produced slightly lower soil water storage than SM and NM did from tasseling to ripening stage (15 August–23 September), which is probably due to relatively high plant transpiration. But in 2016, the values of soil water storage under RPFS, RP and SM treatments were still mildly higher but close to those under NM treatment from tasseling to ripening stage. One possible explanation for this difference is that severe drought at the tasseling stage in 2016 constrained the growth and subsequent transpiration of dryland maize. At the same time, the soil water storage was higher under NM and SM than under RPFS and RP on 22 September 2016, which was attribute to a heavy rainfall before this date.

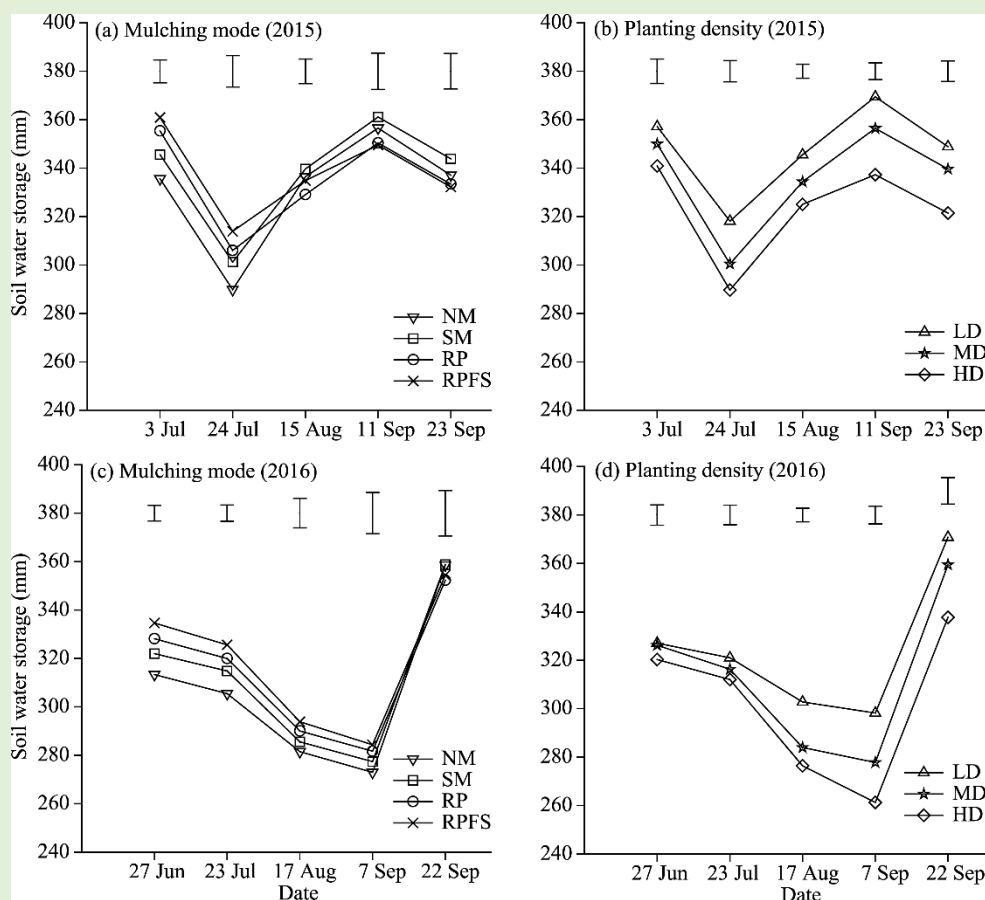


Fig. 7 Soil water storage of dryland maize under different mulching modes and planting densities in 2015 and 2016. Error bars represent standard deviations. Vertical bars indicate significant difference at $P < 0.05$ level.

Compared with LD, the averaged soil water storage under MD and HD was decreased by 11.4 and 23.6 mm in the two experimental years, respectively. Soil water storage generally decreased as increasing planting density, which can be attributed to high soil water consumption and low amount of net rainfall (Tokatlidis et al., 2011). As shown in Figure 7, differences of soil water storage existed among different planting densities at the growth stages of dryland maize.

Table 1 Maize yield including its components, net rainfall, ET and WUE under different treatments of mulching mode and planting mode and planting density, and least significant differences among these treatments in 2015 and 2016

Treatment	Head length (cm)		Seed number per head		1000-Seed weight (kg)		Grain yield (kg/hm ²)		Net rainfall (mm)		ET (mm)		WUE (kg/(hm ² ·mm))	
	2015	2016	2015	2016	2015	2016	2015	2016	2015	2016	2015	2016	2015	2016
Mulching mode														
NM	13.47 ^a	9.39 ^b	308.7 ^b	120.2 ^b	0.247 ^b	0.135 ^b	4910.1 ^b	815.5 ^b	235.8 ^a	228.1 ^a	213.9 ^a	177.1 ^a	23.46 ^c	4.59 ^b
SM	14.45 ^{ab}	9.84 ^b	325.9 ^{ab}	136.1 ^b	0.253 ^{ab}	0.150 ^b	5311.6 ^b	1181.7 ^b	232.7 ^a	224.3 ^a	208.8 ^a	169.2 ^a	25.36 ^{bc}	6.96 ^b
RP	14.84 ^{ab}	12.37 ^a	358.5 ^{ab}	259.2 ^a	0.261 ^a	0.207 ^a	6054.9 ^a	3097.9 ^a	228.8 ^a	219.4 ^a	200.2 ^a	170.6 ^a	30.29 ^{ab}	18.36 ^a
RPFS	15.43 ^b	13.04 ^a	370.5 ^a	269.9 ^a	0.263 ^a	0.214 ^a	6260.0 ^a	3278.2 ^a	225.4 ^a	217.2 ^a	204.7 ^a	171.5 ^a	30.66 ^a	19.59 ^a
Planting density														
LD	15.24 ^a	12.62 ^a	393.3 ^a	253.3 ^a	0.272 ^a	0.202 ^a	4549.6 ^c	2135.0 ^b	239.3 ^a	235.4 ^a	210.3 ^a	168.1 ^a	21.89 ^c	12.75 ^b
MD	14.36 ^{ab}	11.12 ^b	379.5 ^a	221.0 ^a	0.256 ^b	0.186 ^b	6934.4 ^a	2755.1 ^a	230.5 ^{ab}	222.3 ^b	209.9 ^a	173.6 ^a	33.36 ^a	16.45 ^a
HD	14.04 ^b	9.74 ^c	250.0 ^b	114.7 ^b	0.240 ^c	0.144 ^c	5418.4 ^b	1389.9 ^c	222.2 ^b	208.9 ^c	200.5 ^a	174.5 ^a	27.08 ^b	7.92 ^c
Mulching mode×Planting density														
NM×LD	14.25 ^{bc}	10.90 ^{da}	359.6 ^{ab}	140.5 ^b	0.260 ^{bc}	0.167 ^{bcd}	4065.7 ^a	546.8 ^a	244.9 ^a	241.7 ^a	239.6 ^a	178.8 ^{ab}	16.99 ^d	3.07 ^f
NM×MD	13.37 ^{bc}	9.43 ^{fe}	337.7 ^{bc}	133.2 ^b	0.251 ^{bcd}	0.155 ^{cd}	5936.0 ^b	1366.9 ^d	235.5 ^{ab}	229.1 ^{abc}	207.1 ^{bc}	181.4 ^{ab}	29.11 ^b	7.58 ^{da}
NM×HD	12.81 ^c	7.83 ^b	228.9 ^d	87.0 ^c	0.230 ^e	0.083 ^a	4728.7 ^d	532.9 ^a	227.1 ^{ab}	213.5 ^{cd}	195.1 ^c	171.1 ^{abc}	24.28 ^{bc}	3.11 ^f
SM×LD	15.04 ^{ab}	11.21 ^{de}	381.6 ^{ab}	154.7 ^b	0.268 ^{ab}	0.167 ^{bcd}	4358.4 ^{de}	995.38 ^{de}	242.2 ^a	236.8 ^{ab}	204.3 ^{bc}	154.3 ^c	21.37 ^{cd}	6.46 ^{ef}
SM×MD	14.24 ^{bc}	9.98 ^{ef}	359.1 ^{ab}	145.0 ^b	0.254 ^{bcd}	0.164 ^{cd}	6501.3 ^b	1505.4 ^d	232.2 ^{ab}	226.1 ^{abcd}	223.8 ^{ab}	186.2 ^a	29.08 ^b	8.15 ^{de}
SM×HD	14.07 ^{bc}	8.33 ^{gh}	237.0 ^d	108.7 ^b	0.238 ^{de}	0.119 ^{de}	5075.0 ^c	1044.2 ^{de}	223.5 ^{ab}	209.9 ^{de}	198.3 ^{bc}	167.0 ^{abc}	25.63 ^{bc}	6.28 ^{ef}
RP×LD	15.23 ^{ab}	13.82 ^{ab}	408.7 ^{ab}	347.6 ^a	0.277 ^a	0.233 ^{ab}	4743.3 ^{cd}	3354.8 ^a	236.1 ^{ab}	232.2 ^{abc}	193.0 ^c	169.7 ^{abc}	24.60 ^{bc}	19.97 ^b
RP×MD	14.80 ^{abc}	12.22 ^{cd}	402.3 ^{ab}	300.0 ^a	0.258 ^{bc}	0.209 ^{abc}	7537.3 ^a	3915.5 ^{ab}	228.4 ^{ab}	218.8 ^{cd}	203.5 ^{bc}	168.4 ^{abc}	37.28 ^a	23.44 ^{ab}
RP×HD	14.49 ^{abc}	11.07 ^{de}	264.6 ^{cd}	130.0 ^b	0.247 ^{cd}	0.179 ^{abcd}	5884.0 ^b	2023.3 ^c	221.7 ^{ab}	207.1 ^a	204.2 ^{bc}	173.5 ^{abc}	28.98 ^b	11.67 ^c
RPFS×LD	16.45 ^a	14.56 ^a	423.1 ^a	370.6 ^a	0.282 ^a	0.241 ^a	5031.0 ^c	3642.8 ^b	233.9 ^{ab}	231.1 ^{abc}	204.6 ^{bc}	169.7 ^{abc}	24.62 ^{bc}	21.49 ^b
RPFS×MD	15.04 ^{ab}	12.86 ^{cd}	418.8 ^a	305.7 ^a	0.261 ^{bc}	0.216 ^{abc}	7763.0 ^a	4232.7 ^{ab}	225.7 ^{ab}	215.3 ^{de}	205.1 ^{bc}	158.4 ^{bc}	37.95 ^a	26.64 ^a
RPFS×HD	14.79 ^{abc}	11.72 ^{cd}	269.7 ^{cd}	133.3 ^b	0.246 ^{cd}	0.185 ^{abcd}	5986.0 ^b	1959.0 ^c	216.6 ^a	205.2 ^a	204.5 ^{bc}	186.3 ^a	29.42 ^b	10.63 ^{cd}
Factor														
Year	Head length		Seed number per head		1000-Seed weight		Grain yield		Net rainfall		ET		WUE	
	2015	2016	2015	2016	2015	2016	2015	2016	2015	2016	2015	2016	2015	2016
0.000**														
Mulching mode (M)	0.007**	0.000**	0.015*	0.000**	0.004**	0.000**	0.000**	0.000**	ns	ns	ns	ns	0.000**	0.000**
Planting density (D)	0.033*	0.000**	0.000**	0.000**	0.000**	0.001**	0.000**	0.000**	0.010*	0.000**	ns	ns	0.000**	0.000**
M×D	ns	ns	ns	0.002**	ns	ns	ns	0.000**	ns	ns	0.012*	0.021*	ns	0.000**

Note: NM, flat cultivation with non-mulching; SM, flat cultivation with straw mulching; RP, plastic-covered ridge with bare furrow; RPFS, plastic-covered ridge with straw-covered furrow; LD, low planting density of 45,000 plants/hm²; MD, medium planting density of 67,500 plants/hm²; HD, high planting density of 90,000 plants/hm². ET, seasonal evapotranspiration; WUE, water use efficiency. Different lowercase letters in the same column indicate significant difference at $P < 0.05$ level for the same treatment group. * means significant difference at $P < 0.05$ level, and ** means significant difference at $P < 0.01$ level.

3.4 Effects of mulching mode and planting density on grain yield and crop water use

3.4.1 Grain yield and its components

On average across all treatments, the head length, seed number per head, 1000-seed weight and grain yield of dryland maize were 14.6 cm, 340.9, 0.26 kg and 5634.1 kg/hm² in 2015, respectively (Table 1). The corresponding values were 11.2 cm, 196.3, 0.18 kg and 2093.3 kg/hm² in 2016, respectively. Soil mulching, irrespective of planting density, obviously increased the head length, seed number per head, 1000-seed weight and grain yield of dryland maize compared with non-mulching, especially in 2016. Grain yields of dryland maize were 66.6%, 59.9% and 13.4% higher under RPFS, RP and SM than under NM. The effects of mulching mode on grain yield and its components of dryland maize exhibited similar trends during each year of the experimental period. The lowest grain yield of dryland maize, on average 815.5 kg/hm², was recorded under NM. The low grain yield under NM was largely due to the inefficient soil water supply resulted from high unproductive evaporation (Bu et al., 2013). As shown in Table 1, mulching mode had no significant influence on net rainfall input beneath the maize canopy, and net rainfall under NM was not significantly increased compared with other three mulching modes.

Planting density significantly affected the grain yield and its components of dryland maize (Table 1). The head length, seed number per head and 1000-seed weight decreased as plant density increased from LD to HD, whereas the grain yield was highest under MD. Compared with LD, MD and HD increased the grain yield by 52.4% and 19.1% in 2015, respectively. However, in 2016, the grain yield was 29.0% higher and 34.9% lower under MD and HD than under LD, respectively. Maize yield can be improved from the increased optimum planting density instead of the improved grain yield per maize plant (Tokatlidis and Koutroubas, 2004). But, it should be noted that the competition for assimilates between maize plants may be large at high planting density, which, in turn, lead to a reduction in grain yield components (Echarte et al., 2000; Sangoi et al., 2002). In agricultural production, the planting density lower than the optimum one will delay the canopy closure and decrease the interception of solar radiation and gross rainfall, thus leading to a high grain yield per plant and a low grain production per area (Abuzar et al., 2011). In this study, there were no significant interactions between mulching mode and planting density on any of the above traits in both years, except the seed number per head and grain yield in 2016 (Table 1). Yield was significantly affected by planting year. This was mainly due to the characteristics of rainfall, which had a highly uneven distribution in 2016. Much lower net rainfall input at the tasseling stage in 2016 constrained the growth of dryland maize.

3.4.2 Crop water use and water use efficiency (WUE)

The effects of mulching mode and planting density on crop water use of dryland maize were not significant, but the interaction of mulching mode×planting density on crop water use was significant in both years (Table 1). Compared with the three mulching modes, non-mulching treatment generally produced a slightly high crop water use, but the difference was not significant among the four modes. These results are in good agreement with the findings by Lin et al. (2016), who observed no significant differences in crop water use among different mulching modes. At the early growth stage, dryland maize plants were smaller and the consumption of water was mainly via soil evaporation. Straw and plastic mulching of the soil reduced soil evaporation and thus evapotranspiration. The growth of dryland maize was more vigorous at the middle and late growth stages, in which the great consumption of water resulted in a high crop transpiration and evapotranspiration.

Planting density did not significantly affect the crop water use of dryland maize (Table 1), properly due to the high net rainfall input and soil evaporation under low planting density. Population competition could influence the growth condition and transpiration of single plant (Liu et al., 2016). The crop water use of dryland maize was higher in 2015 than in 2016. Specifically, the crop water use of dryland maize was probably compensated by the evenly distributed rainfall in 2015, when mulching retained water throughout the growing season. In 2016, although mulching conserved more water at the beginning of dryland maize growth, it cannot transpire more water at the end of dryland maize growth due to less soil water content resulted from severe drought.

Table 1 shows clearly that WUE of dryland maize was greater under the three mulching treatments than under non-mulching treatment. Compared with NM in both years, RPFS, RP and SM increased the WUE of dryland maize by 79.2%, 73.5% and 15.3%, respectively. The WUE of dryland maize significantly increased first and then reduced as planting density increased from LD to HD, which was similar to the changes in grain yield of dryland maize. WUE of dryland maize was 19.0% lower under LD than under HD in 2015 and 61.0% higher under LD than under HD in 2016. MD had the highest WUE of dryland maize in both years. Mulching mode and planting density significantly affected the WUE of dryland maize in both years, and also their interactions in 2016 (Table 1). The highest WUE (37.95 kg/(hm²·mm) in 2015 and 26.64 kg/(hm²·mm) in 2016) was recorded under the combination of RPFS and MD. There was no significant difference of WUE between RP×MD and RPFS×MD. Soil mulching did not significantly change the net rainfall input but it could conserve more soil water by reducing unproductive evaporation (Ren et al., 2008; Wang et al., 2011). Planting density can balance the soil water competition by adjusting crop population structure. As a result, there may be more water available for promoting the growth and development of maize, which further results in a greater WUE in dryland areas of northern China.

4 Conclusions

The cumulative throughfall, cumulative stemflow and cumulative canopy interception loss during the growing season of dryland maize respectively accounted for 42.3%–77.5%, 15.1%–36.3% and 7.4%–21.4% of the gross rainfall in the two experimental years (2015 and 2016). During the two years, mulching mode had no significant impact on net rainfall, whereas planting density significantly affected net rainfall. Soil mulching can retain more soil water for dryland maize without reducing the net rainfall input beneath the canopy, which may alleviate the contradiction between soil water consumption increase due to the increased planting density and insufficient rainfall input. Based on the results of this study, we recommend that application of medium planting density (67,500 plants/hm²) under plastic-covered ridge with bare furrow could be adopted for dryland maize production on the Loess Plateau of China. In addition, this study can provide a scientific basis for the theory of hydrological cycle in dryland agriculture, and also provide a guidance for the development of suitable agronomic practices to improve the water use efficiency of crop on the Loess Plateau, as well as in the other similar regions.

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